Progress Report: Arctic Regional Reanalysis (NOAA Grant NA17RT1224)

Period covered: 1 October 2003 – 31 March 2004

The following is a report of progress toward the Arctic System Reanalysis (ASR), for which work has been initiated under NOAA Grant NA17RT1224 to the Cooperative Institute for Arctic Research. We summarize progress in each of the three main components of the project: (1) Adaptation of the new WRF (Weather Research and Forecasting Model) to the Arctic, (2) Data assimilation tests for the Arctic, and (3) Assessments of the Arctic output of existing reanalyses, particularly the recently released ERA-40 global reanalysis.

Highlights of the past six months include the following. The WRF model has been implemented on an Arctic domain and has been found to produce Arctic forecasts of similar quality to Polar MM5, even without the inclusion in WRF of MM5's polar enhancements. The importance of observations from Greenland has been indicated by early tests. The need for attention to the error covariances used in the Arctic has also been shown by assimilation experiments with MM5. Evaluations of the recent ERA-40 global reanalysis show that the Arctic cloud and radiative flux fields are substantially more realistic than in the NCEP/NCAR global reanalysis, implying that appropriate parameterizations for these quantities will be achievable in ASR. However, examinations of the precipitation, temperature and circulation fields have revealed a need for attention to the procedure by which the TOVS radiances are utilized. Details on these and other findings are provided in the following sections (1)-(3), which correspond to the three main project components.

(1) Adaptation of WRF (Weather Research and Forecasting) model for the Arctic (Bromwich, Hines)

Groundwork has been laid for a planned state-of-the-art assimilation of atmospheric and other environmental data. . First, the Weather Research and Forecasting (WRF) model, currently in the late stages of development by a collaboration of multiple agencies, is being adapted for the Arctic. We will be seeking a package of parameterizations optimized for polar applications. An early version of WRF was obtained by the Polar Meteorology Group (PMG) of the Byrd Polar Research Center at The Ohio State University. This version runs on the PMG's Linux cluster. The model was first tested for July and December, 2002 on an Arctic grid similar to that used for PMG's current mesoscale Arctic studies with the earlier Polar MM5. The stability of the simulations was found to be sensitive to the selection of turbulence and boundary layer parameterization and the specifications of the upper boundary treatment. Once a stable configuration was found, the Arctic forecasts with WRF produced synoptic-scale fields of similar quality to that of Polar MM5 simulations. This is an encouraging early finding as the polar enhancements for MM5 have not yet been implemented into WRF. Next, WRF is being evaluated with high-resolution mesoscale simulations over Greenland and vicinity. Previous work comparing MM5 with *in-situ* observations has shown that the Greenland domain represents an ideal opportunity to test and improve the physical parameterizations for mesoscale polar simulations.

A 28-level version of WRF with 40 km horizontal resolution has been tested for winter Greenland conditions. Diffusion and boundary layer physics are based upon parameterizations adapted from the NCEP ETA model. Output from the NCEP Aviation Model is used for initial and boundary conditions. A series of 2-day simulations were performed starting each day at 0000 UTC during the test period. It appears that the initial conditions would be substantially improved if local Greenland observations were assimilated. A comparison against automatic weather station (AWS) data suggests that enhancements are needed for the polar boundary layer, as was previously done with MM5. An updated WRF (version 2.0) will be released in May 2004. It will include a new microphysics package and fractional sea ice. We are also working on improving the treatment of the horizontal pressure gradient force for the non-hydrostatic mesoscale simulations, applicable to both MM5 and WRF.

(2) Data assimilation tests on MM5 and WRF (Tilley, Fan)

The first steps toward a data assimilation system for the ASR have been taken with the MM5 models. The strategy being followed is to test the assimilation procedure (including different formulations of error covariances) and data sensitivities by using the well-documented MM5 regional forecast model on domains covering Alaska and the surrounding ocean areas. Test cases have been selected, and preliminary runs have already made with MM5. The test cases include "generic" periods of several days from each of the four seasons, and three examples of "extreme events": (1) a major snowstorm affecting the Anchorage area in March 2002; the localized nature of the snow in this case implies that high resolution is necessary but not necessarily sufficient to capture the details of the event; (2) a major summer rain event in July 2003 that produced record rainfall (3-4 inches in 24 hours) and flooding in the Tanana Valley area of interior Alaska; and (3) a strong cyclonic storm event that produced high winds and coastal flooding along the northwestern coast of Alaska in September 2003. Each of the generic cases and the extreme event cases will be run on either a coarser-resolution pan-Arctic domain at coarse/fine resolutions of 60 km/30 km, or on a smaller Alaskan domain at coarse/fine resolution of 45/15 km.

As of mid-March, the summer and autumn cases have been run for a control case (using the standard MM5 pre-processor) and with the so-called "3D-VAR" approach in which a model forecast provides an initial guess for the state from which a forecast is made after the assimilation of observational data. Experiments with the summer and autumn cases have already shown that there are substantial impacts of the background error covariance on the 3D-VAR performance. Thus we have already established that the Arctic is not insensitive to the error covariances used in a data assimilation cycle.

In additional work performed under the subcontract to Jeff Tilley, WRF is now running on a LINUX cluster at the University of North Dakota. In addition, a version of WRF will be running on the Cray X-1 at the University of Minnesota by May. Tilley has visited the University of Alaska twice during the past few months for coordination of the data assimilation tasks.

(3) Assessment of ERA-40 performance in the Arctic (Serreze, Bromwich, Hines, Walsh)

Precipitation from ERA-40 (Serreze)

Precipitation forecasts from the ERA-40 reanalysis were examined for the region north of 45°N, the large Arctic-draining watersheds and the central Arctic Ocean. Comparisons were made with corresponding forecasts from the NCEP/NCAR reanalysis, the earlier ERA-15 effort as well as satellite retrievals from the GPCP (Global Precipitation Climatology Project). The focus was primarily on monthly precipitation evaluated with respect to gridded fields of station data. For each reanalysis, the evaluations used 6-hourly accumulated precipitation from 12-hour forecasts. Use was made of the low-resolution (2.5 degree) ERA-40 fields that are now available at ECMWF and NCAR. We emphasized the period 1979-1993 common to all of the precipitation estimates. While the high-latitude gauge network is degraded in later years, it is sparse even for this 15-year period. A manuscript detailing results from this study is slated for submission to *Monthly Weather Review* in early April.

Depictions of monthly precipitation from ERA-40 are greatly improved over those from NCEP/NCAR. This is with respect to both biases and squared correlations between modeled and observed grid cell time series. The former conclusion must be interpreted with the caveat that the observations include significant bias adjustments, primarily for gauge under-catch of solid precipitation. In turn, even NCEP/NCAR provides higher squared correlations than those from the GPCP effort. There is no evidence that the GPCP retrievals are improved after 1987 when the retrievals began to use TOVS data.

Over large parts of the Arctic landmass, squared correlations observed and ERA-40 precipitation exceed 0.50 and are locally higher. However, there are large areas where squared correlations are low. On the scale of the large Arctic-draining watersheds (the Ob, Yenisey, Lena and Mackenzie), squared correlations between ERA-40 and observed monthly precipitation typically range from 0.60-0.90. In general, ERA-40 performance declines in summer. This is expected, as part of the precipitation is of convective origin. Convective precipitation tends to be localized.

Some sense of model performance over the central Arctic Ocean can be obtained from comparisons with measurements from the Russian North Pole (NP) program that ended in 1991. ERA-40 performance seems to be poor in this region for winter and spring. Performance is better in summer and autumn. This is also true for NCEP/NCAR, ERA-15 and the GPCP product. In large part, this appears to be a reflection of the higher precipitation in summer and autumn, such that the signal to noise ratio is higher.

While we are pleased at the overall performance of ERA-40 relative to NCEP/NCAR, we are nevertheless led to the sobering conclusion that ERA-40 offers no obvious improvement over ERA-15. ERA-15 actually performs better in summer. This may relate to difficulties in assimilation of satellite radiances. In an earlier pilot study using several years of data from a pre-production run of ERA-40, a strong cold bias was noted in the troposphere, centered over the ice-covered Arctic Ocean, presumably with adverse impacts on precipitation. This was traced to problems in the assimilation of TOVS radiances. The issue was addressed in the production run of ERA-40, but we suspect that problems still exist. This underscores the need to pay careful attention to the use of satellite data in the ASR. It is important to note that in contrast to ERA-40, ERA-15 assimilated derived TOVS profiles (temperature and humidity).

2m temperatures from ERA-40 (Serreze)

Forecasts of 2-m temperatures (taken here to represent surface air temperature, or SAT) from ERA-40 were evaluated for the region north of 60°N). ERA-40 temperatures were compared with SAT data from the International Arctic Buoy Program/Polar Exchange at the Sea Surface (IABP/POLES) data set. The IABP-POLES data set blends SAT observations from buoys, the NP program and land stations for the period 1979 to 1997, and hence covers the years for which ERA-40 draws from a modern satellite data base. Optimal Interpolation is used to blend the different data sources into 12 hour fields (00:00 and 12:00 UTC) on a 100 km rectangular grid. This blended product provides the best estimate of SAT for the region.

We used the high-resolution ERA-40 fields provided on the N80 quasi-regular Gaussian grid (roughly 1 degree resolution). These were obtained through collaboration with investigators at the British Antarctic Survey (BAS). Only the 2.5° x 2.5° ERA-40 fields are available to the general public at present. SAT data for 00:00 and 12:00 UTC for the period 1979 to 1997 were re-gridded to IABP/POLES 100 km grid.

Monthly bias fields of ERA-40 SAT were computed with respect to monthly means from the IABP/POLES data set. Grid cells in the IABP/POLES data set with less than 30 observations were not used in the analysis. This excludes much of the land area between November and April. The IABP/POLES data set is also data poor in areas such as the North Atlantic, Barents and East Greenland Seas and over central Greenland.

In general, biases for the central Arctic Ocean (where data coverage is best) are between -3º C and 3º C in all months. In spring, ERA-40 temperatures are slightly warmer than IABP/POLES around the Pole. Cold biases appear off the north Greenland coast and in the East Siberian Sea between November and January. Land regions appear to have cold bias between April and October. While further investigation is needed, the land biases may occur because of late snow melt in the ERA-40 model. . A persistent warm bias is present in the North Atlantic and Barents, Greenland and Norwegian Seas for much of the year. Central Greenland has a persistent cold bias throughout the year. But as mentioned, these areas are data-poor in the IABP/POLES data set.

Gridded times series from ERA-40 and IABP/POLES were correlated for the period 1979 to 1997. In general, air temperatures for April through September for land areas are well correlated (greater than 0.6). Strong positive correlations are found over the Arctic Ocean in April and May. However, temperatures are not so well correlated for ocean regions and Greenland between June and August. The poor summer correlations over the Ocean are not surprising. Because of the melting ice surface, the observed and modeled temperatures hover about the freezing point, and the temporal variance is small.

Cloud and radiation fields from ERA-40 (Walsh)

The fields of cloudiness and surface radiation are likely to be among the most widely used products of an ASR For these reasons, we are paying particular attention to the Arctic cloud and radiation fields produced by recently completed reanalyses. During the past several months, we have examined the ERA-40 reanalysis of the following fields: total cloudiness, surface solar radiation, surface longwave radiation, net surface radiation and cloud radiative forcing. These fields have been evaluated on a monthly basis for a domain centered on the North Pole and extending equatorward to 45˚N. They are available on-line at http://arctic.atmos.uiuc.edu/ERA40/.

The reanalyzed fields of cloudiness show remarkable fidelity to the observations over the Arctic Ocean, where cloud fractions range from about 0.5 in the winter to values greater than 0.9 during the summer. This seasonal cycle has improved since ERA-15, and it is superior to the seasonal cycle in the NCEP/NCAR reanalysis. The only deficiencies appear to be somewhat too high values over the subpolar North Pacific and much of Alaska during summer, and a rather structured pattern over Greenland for which there is little evidence in other data sources.

The fields of net surface solar radiation are also very consistent with observational measurements over the Arctic. While the values are close to zero over most of the Arctic during the winter months, summer daily averages range from approximately 100 W m^{-2} over the ice-covered central Arctic Ocean to 150-225 W m^{-2} over Arctic and subarctic land areas. The mean June value of 175 W m^{-2} at Barrow corresponds closely to the mean June value obtained from measurements at the ARM/NSA site. The signature of sea ice is prominent in the fields of net solar radiation, a consequence of the attention paid to details of sea ice coverage by the ECMWF personnel.

The net surface longwave radiation (shown as positive upward at http://arctic.atmos.uiuc.edu/ERA40/), follows closely the distribution of surface temperature in time and space. The fields are generally more smoothly varying than the fields of surface solar radiation, and their seasonal cycle has a much smaller amplitude than that of the surface solar radiation. While validation data are limited, the seasonal range from ~40 W m^{-2} in January to ~60 W m^{-2} in July at Barrow, well with the ARM/NSA measurements. The fields of net total (solar + longwave) surface radiation show a pattern that is generally symmetric about the Pole. Annual mean values of the net total surface radiation are positive equatorward and negative poleward of about 70˚N (in contrast to the radiative budget for the surface-atmosphere system, for which the zero crossing is at about 40˚N).

Finally, the cloud-radiative forcing at the surface has been evaluated in terms of the ERA-40 departures from clear-sky net surface radiation as a function of cloud fraction and calendar month. (The integral of this difference over all sky conditions would be the cloud-radiative forcing as conventionally defined). Clouds have large (40-50 W m^{-2}) impacts on net surface radiation in ERA-40, although these occur only when the cloud fraction exceeds 0.9. Partial cloud fractions of 0.1 to about 0.9 generally modify the surface fluxes by less than about 15 W m^{-2}. The overall cloud-radiative forcing is positive from September-October through May and negative from June through at least early August. This seasonality of the sign of the cloud-radiative forcing is consistent with corresponding values based on cloud and radiation measurements made at the Russian NP drifting stations (Chapman and Walsh, 1998, *J. Climate*), and is longer than the 4-6 weeks obtained by Curry and Ebert (1992, *J. Climate*). The seasonal forcing integrated over cloud fraction is generally consistent in magnitude and sign with the recent analysis of AVHRR Polar Pathfinder (APP) products by Wang and Key (2003, *Science*).

Atmospheric circulation in ERA-40 (Bromwich, Hines)

The PMG has also been examining the Arctic atmospheric circulation diagnosed by ERA-40. Previous research has revealed some significant differences between reanalysis winds from ERA-15 and NCEP-NCAR and those measured by independent rawinsonde observations (CEAREX) from the Atlantic Arctic (Francis, *Geophys. Res. Letts.*, **29** (9), 1-4, 2002). This comparison has been re-evaluated and extended to ERA-40. As essentially found before, the reanalysis winds on average are too westerly and too northerly with the differences maximized in the middle and upper troposphere; ERA-40 is very similar to ERA-15 and NCEP-NCAR in this regard. However, this new analysis has revealed that ERA-40 and ERA-15 capture the observed day-to-day wind variability much better than NCEP-NCAR. In addition, comparisons have been made between ERA-15 and ERA-40 over the overlap period of 1979-1993. As found by Bromwich et al. (ERA-40 Project Report Series # 3, 287-298, 2002), the average 500-hPa heights in ERA-40 are ~30 geopotential meters lower than ERA-15 over the central Arctic due to slightly cooler lower tropospheric temperatures in ERA-40 than observed. It is known that this is due to ERA-40 difficulties in assimilating TOVS radiances over Arctic sea ice and leads to enhanced summer precipitation over the central Arctic in ERA-40 (found by Serreze and Etringer, ERA-40 Project Report Series # 3, 317-332, 2002). The anomalous geostrophic winds implied by the 500-hPa height differences between ERA-40 and ERA-15 are consistent with the above comparison between reanalysis winds and CEAREX observations. A paper is in preparation for the *J. Climate* (Evaluation of the ECMWF 15/40 and NCEP/NCAR reanalyses over the over the data sparse Arctic Ocean, by Bromwich, Wang, and Francis) describing this work.